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REDUCTION OF VAPOR CARRYUNDER IN SIMULATED BOILING

by

P. L. Miller and C. P. Armstrong

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REDUCTION OF VAPOR CARRYUNDER IN SIMULATED BOILING

by

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and
Associated Midwest Universities

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REDUCTION OF VAPOR CARRYUNDER IN SIMULATED BOILING

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ABSTRACT

This report describes the effect on vapor carryunder in simulated boiling caused by insertion in the flow stream of several different geometric configurations and sizes of wire screens. The effect on vapor carryunder caused by screen location and mesh size is shown to be closely related to other system variables. The relationship among the most significant variables is shown in a series of graphs. Significant reduction of vapor carryunder is achieved under certain conditions.

Data verifying a correlation given in ANL-6581 for different system geometries are included as an appendix.

NOMENCLATURE

Variables

A	area
D	diameter
G	mass velocity
g	gravitational constant
g_c	conversion constant
H	height of free surface above riser (interface height)
L	length
lb_m	pounds mass
lb_f	pounds force
R	radius dimension
V	velocity
$\dot{W}$	flow rate

X	quality
α	void volume fraction
ρ	density
μ	viscosity
σ	surface tension

Subscripts

1	section at outlet of riser
D	downcomer
ent	entrapped
g	gas
ℓ	liquid
R	riser
S	superficial
T	total

I. INTRODUCTION

During the past two years a study of the factors affecting vapor carryunder in boiling and simulated boiling systems has been in progress at Argonne National Laboratory. The need for such a study is specific in a two-phase system where the fluid is circulated. In a natural-circulation system, the vapor phase entrapped in the recirculating liquid will reduce the density head which is the driving mechanism for circulation. If carryunder is severe enough, the efficiency of the system will be considerably reduced and burnout may result. In a forced-circulation system, the presence of vapor in the recirculating fluid will reduce efficiency and may cause cavitation problems in the pumping apparatus.

The purpose of the present investigation is to find some method of reducing the vapor carryunder with mechanical devices inserted in the flow stream. For the initial studies, it was decided to use an air-water system to simulate natural boiling and to limit the mechanical devices to wire screens of various mesh sizes and geometric configurations.

II. LABORATORY APPARATUS

As illustrated in Fig. 1, the air-water simulated boiling system consisted of a circulating pump, an air-injection system, the test section or separating plenum, and an air-water separating tank.

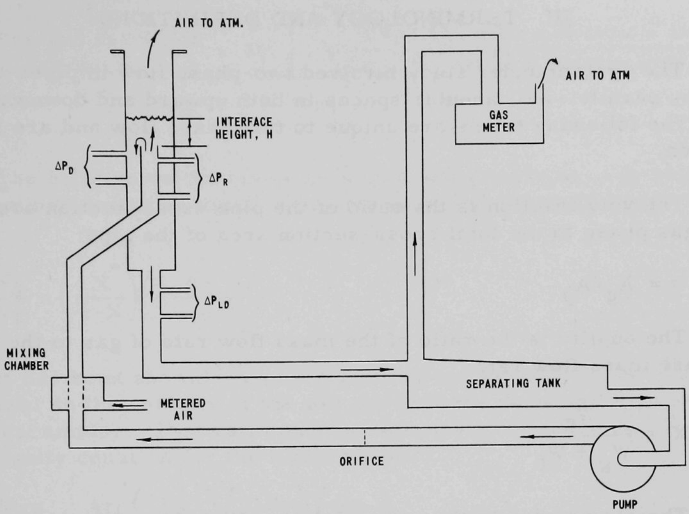


Fig. 1. Schematic of Laboratory Apparatus

Water was circulated through the loop with two pumps having a combined capacity of approximately 300 gpm. The flow rate was regulated with a bypass system and metered with a thin-plate orifice. The air-injection system supplied a desired quantity of air which was metered with a thin-plate orifice. The air flowed radially through approximately 300 small holes in the wall of the water pipe to mix with the water. The mixture then passed up the riser into the test section where the major portion of the air was separated at the free interface and released to the atmosphere. The remaining air was entrapped by the liquid which recirculated down the annular space between the riser and outer tube. This annular space is referred to as the downcomer. Both the riser and outer tube were Lucite plastic pipe so the process was fully visible.

The water, carrying with it the entrapped air or carryunder, then passed through a separating tank where the liquid velocity was greatly decreased. This allowed the air to separate from the liquid and pass up through a large vertical pipe to a cumulative-type gas meter where the volumetric flow rate was measured. The air was released to the atmosphere and the water returned to the pumps to repeat the cycle.

The operating procedure was to set the desired air and water flow rates and the interface height above the top of the riser and allow the loop to come to equilibrium. Temperature control was maintained with jacket-type heat exchangers.

III. TERMINOLOGY AND DEFINITIONS

The system under study involved two-phase flow in pipes and circular, parallel-wall annular spaces in both upward and downward directions. The following terms are unique to two-phase flow and are in need of definition.

The void fraction is the ratio of the pipe cross-section area filled by the gas phase to the total cross-section area of the pipe:

$$\alpha = A_g/A_p \quad . \tag{1}$$

The quality is the ratio of the mass flow rate of gas to the total two-phase mass flow rate:

$$X = \frac{\dot{W}_g}{\dot{W}_g + \dot{W}_\ell} \quad . \tag{2}$$

The carryunder is the ratio of the quality of two-phase mixture in the downcomer to the quality of mixture in the riser. In the range of this study the mass flow rate of the gas phase was much less than the mass flow rate of the liquid phase; therefore, the carryunder was, for all practical purposes, the ratio of gas flow rate in the downcomer to gas flow rate in the riser:

$$\frac{X_D}{X_R} = \frac{\dot{W}_{gD}}{\dot{W}_{gD} + \dot{W}_\ell} \Bigg/ \frac{\dot{W}_{gR}}{\dot{W}_{gR} + \dot{W}_\ell} \approx \frac{\dot{W}_{gD}}{\dot{W}_{gR}} \quad . \tag{3}$$

It has been tacitly assumed that none of the liquid phase was lost to the atmosphere above the interface. Although this is not wholly true, the loss was negligible in comparison with the liquid circulation rate. A baffle arrangement was placed on top of the test section to eliminate mechanical entrapment, so virtually the only liquid that escaped was that necessary to saturate the incoming air in the mixing chamber.

The superficial liquid velocity is that velocity the liquid would have if it filled the pipe completely as in single-phase flow:

$$V_S = \frac{\dot{W}_\ell}{\rho_\ell A_P} \quad . \tag{4}$$

The percent reduction of carryunder is an expression of the difference between a normal system and one with a mechanical device intended to reduce carryunder in place in the flow stream:

$$\text{Percent reduction of carryunder} = 100 \left[1 - \frac{(X_D/X_R) \text{ with mechanical device}}{(X_D/X_R) \text{ without mechanical device}} \right] . \tag{5}$$

The relative velocities of the liquid and gas phase (slip ratio) may be determined from the equation of continuity and the definitions of α and X:

$$\frac{V_g}{V_\ell} = \left(\frac{X}{1-X}\right)\left(\frac{1-\alpha}{\alpha}\right)\frac{\rho_\ell}{\rho_g} . \tag{6}$$

It has been shown[1] that the ratio of the velocity of the gas phase in the riser to the velocity of the gas phase in the downcomer is an important parameter. This ratio may be determined by using Eq. (6) and the continuity equation for the liquid phase:

$$\frac{V_{gR}}{V_{gD}} = \frac{A_D}{A_R}\left(\frac{X_R}{1-X_R}\right)\left(\frac{1-X_D}{X_D}\right)\left(\frac{\alpha_D}{\alpha_R}\right) . \tag{7}$$

IV. MECHANICAL REDUCTION OF CARRYUNDER

In this study, the test section consisted of a $6\frac{1}{2}$-in.-ID, 7-in.-OD Lucite riser inside a $11\frac{1}{8}$-in.-ID Lucite downcomer. The construction of the test section is shown in Fig. 2. Tests were first made with a straight riser with no attachments; then the device to be tested was inserted and the test conditions repeated. Pump size limited downcomer superficial liquid velocity to 1.5 ft/sec.

The ranges of parameters studied were:

Downcomer velocity	V_{SD}	0.9-1.5 ft/sec
Riser quality	X_R	0.0002-0.0013
Height of interface	H	4-19 in.
Area ratio between downcomer and riser	A_D/A_R	1.8

The geometries and screen sizes tested are described in Fig. 3 and Table 1. All had open tops and bottoms and were attached to the top of the riser. Interface heights were measured from the top of the solid riser in all cases.

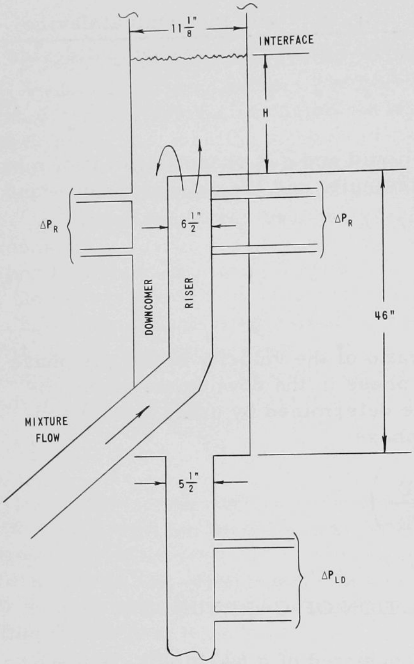


Fig. 2. Cross-sectional View of Test Section

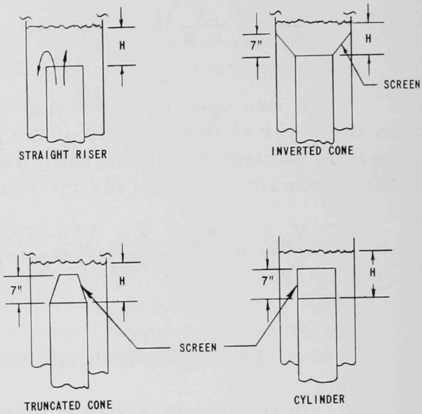


Fig. 3. Riser Geometries

Table 1

SCREEN SPECIFICATIONS

Mesh	Wire Diameter (in.)	Screen Thickness (in.)	Percent Free Area
120 x 120	0.0030	0.007	30.0
100 x 100	0.0045	0.009	30.3
60 x 60	0.0075	0.0015	30.5
40 x 32	0.0075	0.0016	52.7

Perforated metal - with 33 x 29 holes/sq in., 0.020-in. hole diameter; thickness 0.0215 in.; 30.0% free area.

A. Test Results

The results of the tests are shown in Figs. 4 through 10. For a given downcomer superficial liquid velocity V_{SD} and riser quality X_R, the carryunder is plotted versus interface height with riser geometry as a parameter. The upright conical screen and the cylindrical screen, both having 40 x 32 mesh, were of no appreciable value in reducing carryunder and, in some cases, actually increased carryunder as much as 40%. The 100 x 100 mesh upright cone consistently reduced carryunder, but not nearly so much as the 100 x 100 inverted cone, which reduced carryunder more than 50 percent over most of the ranges of parameters studied and often produced an even greater carryunder reduction. The decrease of carryunder with increase of interface height is evident in all cases studied.

Since the inverted-cone geometry seemed to offer the most significant results, tests were run to determine the effect of screen size on that geometry. The results are shown in Fig. 10, in which carryunder is plotted as a function of interface height, and screen size is a parameter. Downcomer superficial liquid velocity and riser quality were held constant for each test. It is evident that the 100 x 100 mesh screen provided the greatest reduction in carryunder of all screen mesh sizes tested.

Figures 11 and 12 show the effect of riser quality and interface height on carryunder for a particular geometry. The results for the straight riser, part of which are given in Fig. 11, show that at all velocities the carryunder decreased for an increase in both riser quality and interface height. This is consistent with Petrick's data.[1] For the 100 x 100 mesh inverted cone geometry (see Fig. 12) the carryunder <u>increased</u> with an increase of riser quality, but decreased with interface height as before.

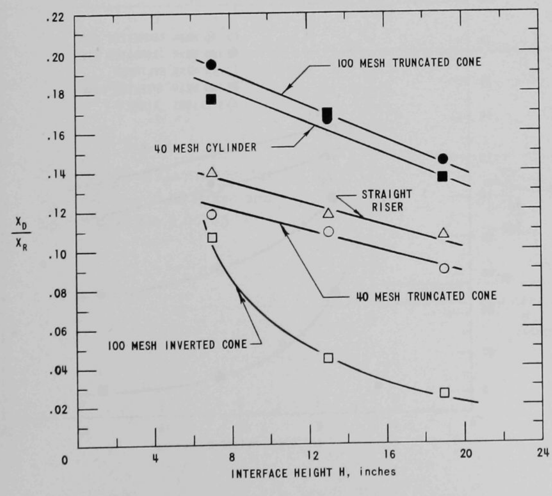


Fig. 4

Comparison of Carryunder for V_{SD} = 1.50 ± 0.05 ft/sec; X_R = 0.00070 ± 0.00005

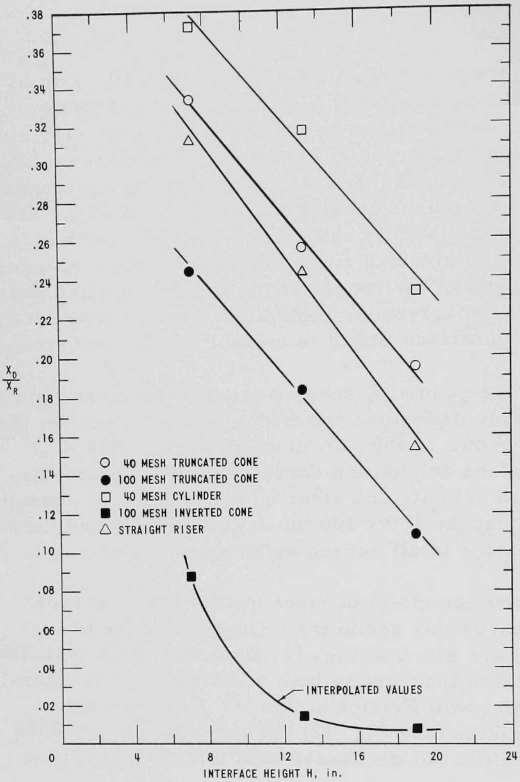


Fig. 5

Comparison of Carryunder for $V_{SD} = 1.50 \pm 0.05$ ft/sec and $X_R = 0.00023 \pm 0.00003$

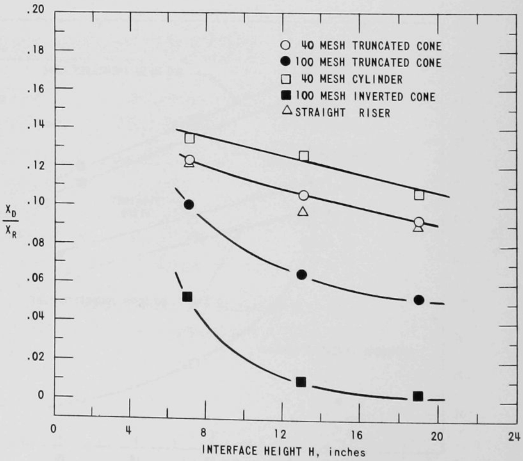


Fig. 6

Comparison of Carryunder for $V_{SD} = 1.25 \pm 0.05$ ft/sec and $X_R = 0.00070 \pm 0.00005$

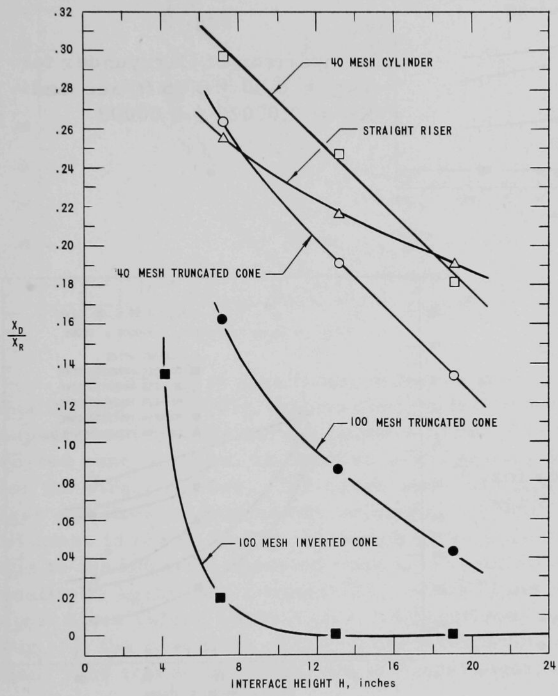


Fig. 7

Comparison of Carryunder for $V_{SD} = 1.25 \pm 0.05$ ft/sec and $X_R = 0.00023 \pm 0.00003$

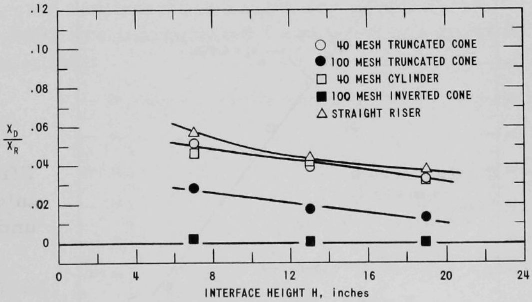


Fig. 8

Comparison of Carryunder for $V_{SD} = 0.90 \pm 0.05$ ft/sec and $X_R = 0.00070 \pm 0.00005$

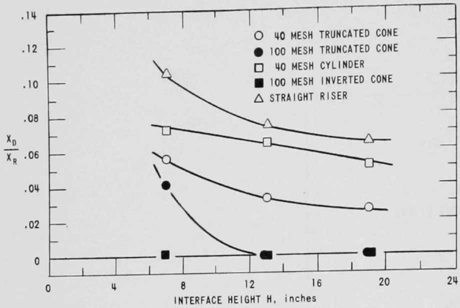


Fig. 9

Comparison of Carryunder for $V_{SD} = 0.90 \pm 0.05$ ft/sec and $X_R = 0.00023 \pm 0.00003$

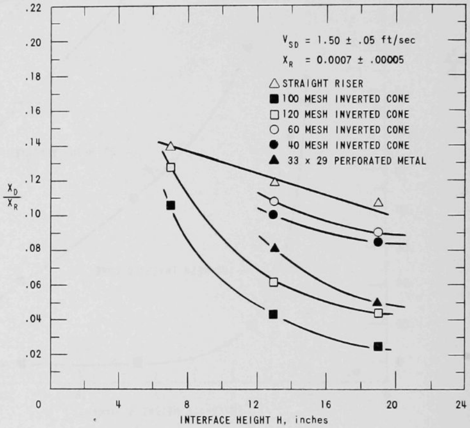


Fig. 10

Comparison of Carryunder for Different Screen Mesh Sizes

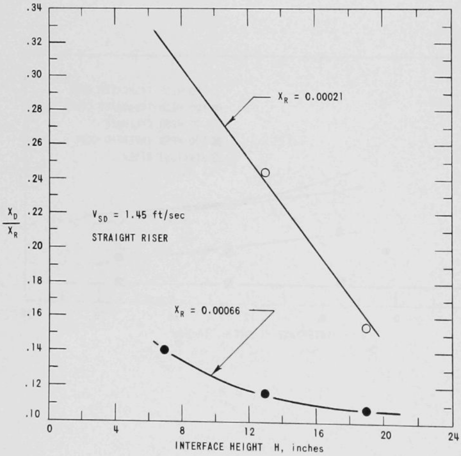


Fig. 11

Effect of Riser Quality and Interface Height on Carryunder, Straight Riser

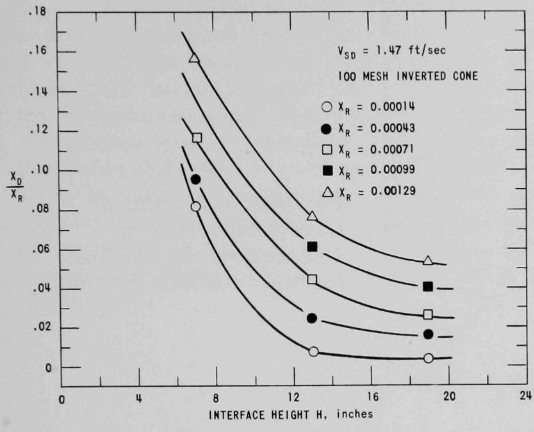


Fig. 12

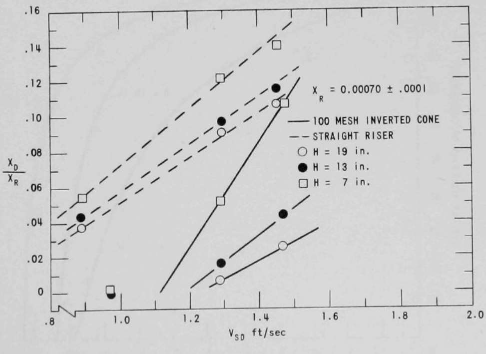
Effect of Riser Quality and Interface Height on Carry-under, 100 Mesh Inverted Cone

Figure 13 is significant in that it shows, for a particular riser quality (X_R = 0.0007), that no carryunder is to be expected at downcomer superficial liquid velocities below 1 ft/sec with the 100 x 100 mesh inverted cone in place, as opposed to the no-carryunder velocity of 0.6 ft/sec for the straight riser. The curve also indicates that the screen becomes less effective as downcomer velocities increase. This decrease in effectiveness is shown in Fig. 14, which gives percent reduction in carryunder due to the 100 mesh inverted cone as a function of downcomer velocity. Riser quality is again held constant (X_R = 0.0007) and interface height is a parameter. Since values above V_{SD} = 1.5 ft/sec are the result of interpolation from Fig. 13, the exactness of the values should not be accepted without qualification. The trends of the curves are most significant and evident.

Figures 15 and 16 show how the percent reduction of carryunder due to the 100 x 100 mesh inverted cone varies with riser quality. Downcomer superficial liquid velocity and interface height are parameters. Again, values above X_R = 0.0007 are interpolated from previous curves but the trends are most significant.

Fig. 13

Effect of Downcomer Superficial Liquid Velocity on Carryunder



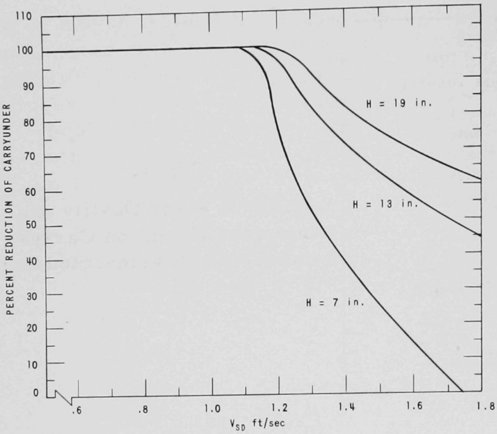


Fig. 14

Percent Reduction of Carryunder Due to 100 Mesh Inverted Cone for $X_R = 0.00070 \pm 0.0001$

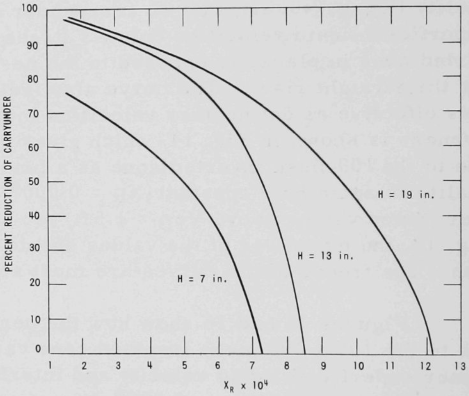


Fig. 15

Percent Reduction of Carryunder Due to 100 Mesh Inverted Cone for V_{SD} = 1.5 ft/sec

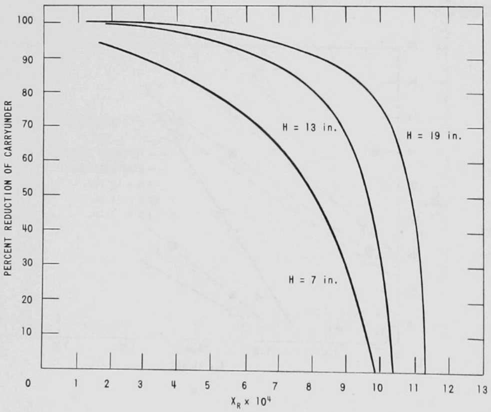


Fig. 16

Percent Reduction of Carryunder Due to 100 Mesh Inverted Cone for V_{SD} = 1.30 ft/sec

In attempting to reduce carryunder with a mechanical device in a natural-circulation loop, it is desirable that the pressure drop across the device be less than, or at most equal to, the resulting increase in driving head. The increase in driving head is a result of there being less vapor in the recirculation leg, thus causing a higher fluid density. In a forced-circulation loop, the pressure losses are not as critical, but still it is desirable that they remain small. Facilities were not available for a study of pressure drop; consequently, the true benefits of these devices, considering the pressure drop, for the reduction of vapor carryunder are not fully known. Under given conditions, however, these devices reduce carryunder significantly enough to make a study of pressure drop worthwhile.

V. CONCLUSIONS

The 100 mesh inverted cone was found to be the geometry and mesh size which most significantly reduced carryunder of those devices tested. Under certain conditions the reduction of carryunder was excellent. The reduction in carryunder decreased with increases in both riser quality and downcomer superficial liquid velocity, and increased with interface height.

APPENDIX A

MECHANICAL REDUCTION OF CARRYUNDER DATA

MECHANICAL REDUCTION OF CARRYUNDER DATA

Riser ID = $6\frac{1}{2}$ in.
Riser OD = 7 in.
Downcomer ID = $11\frac{1}{8}$ in.

Run No.	X_R (x 10^{+3})	H (in.)	$\dot{W}_\ell$ (lb/sec)	X_D/X_R	V_{SD} (ft/sec)	X_D (x 10^{+3})	T_{AIR} (°F)	T_{H_2O} (°F)	Barometric Pressure (in. Hg)
40 x 32 Mesh Truncated Conical Screen on Top of Riser									
387	0.664	19	32.5	0.09305			80.6	90.0	29.40
388	0.658	13	32.8	0.10648			80.6	90.0	↓
389	0.658	7	32.8	0.12268			81.5	90.0	↓
390	0.195	19	32.8	0.13437			81.5	89.5	↓
391	0.192	13	33.2	0.19218			81.6	89.5	↓
392	0.195	7	32.8	0.26406			81.9	89.5	↓
393	0.210	19	37.0	0.19487			82.4	↓	↓
394	0.210	13	37.0	0.25641			82.6	↓	↓
395	0.210	7	37.0	0.33589			82.6	↓	↓
396	0.581	19	37.0	0.14465			83.6	↓	↓
397	0.581	13	37.0	0.16651			84.5	↓	↓
398	0.585	7	36.7	0.19348			84.5	↓	↓
399	0.233	19	23.6	0.02545			84.6	↓	↓
400	0.228	13	24.1	0.03272			84.6	↓	↓
401	0.230	7	23.9	0.05636			84.9	↓	↓
402	0.659	19	24.1	0.03207			85.1	↓	↓
403	0.670	13	23.7	0.03836			85.1	↓	↓
404	0.659	7	24.1	0.05220			85.5	↓	↓
Cylindrical Screen 40 x 32									
405	0.235	19	23.4	0.0511	0.924		88.4	87.0	29.35
406	↓	13	↓	0.0638	↓		↓	88.0	↓
407	↓	7	↓	0.0723	↓		↓	89.0	↓
408	0.679	19	↓	0.0324	↓		↓	90.5	↓
409	↓	13	↓	0.0412	↓		↓	90.5	↓
410	↓	7	↓	0.0471	↓		88.5	91.5	↓
411	0.230	19	32.6	0.182	1.29		81.0	87.5	↓
412	0.230	13	32.6	0.248	1.29		81.2	87.5	↓
413	0.228	7	32.9	0.289	1.30		81.4	87.5	↓
414	0.726	19	32.9	0.107	1.30		82.0	87.5	↓
415	0.720	13	33.2	0.126	1.31		82.1	88.0	↓
416	0.720	7	33.2	0.135	1.31		83.1	88.0	↓
417	0.201	19	37.3	0.233	1.47		83.1	88.0	↓
418	0.201	13	37.3	0.318	1.47		83.1	88.0	↓
419	0.201	13	37.3	0.373	1.47		83.1	88.0	↓
420	0.640	19	↓	0.136	↓		83.3	↓	↓
421	↓	13	↓	0.168	↓		84.0	↓	↓
422	↓	7	↓	0.177	↓		84.6	↓	↓
100 x 100 Truncated Cone									
423	0.639	19	37.4	0.089	1.48	0.057	89.3	87.0	29.40
424	0.639	13	37.4	0.109	1.48	0.070	89.5	87.5	↓
425	0.630	7	37.9	0.119	1.50	0.0751	89.6	↓	↓
426	0.210	19	37.0	0.109	1.46	0.0023	89.9	↓	↓
427	0.206	13	37.3	0.184	1.47	0.0380	89.6	↓	↓
428	0.209	7	37.3	0.245	1.47	0.0512	89.6	↓	↓
429	0.228	19	23.2	0.000	0.916	0.0	90.0	↓	↓
430	0.228	13	23.2	0.000	↓	0.0	90.0	↓	↓
431	0.219	7	23.2	0.0406	↓	0.0089	90.1	↓	↓

MECHANICAL REDUCTION OF CARRYUNDER DATA (Contd.)

Run No.	X_R ($\times 10^{+3}$)	H (in.)	$\dot{W}_\ell$ (lb/sec)	X_D/X_R	V_{SD} (ft/sec)	X_D ($\times 10^{+3}$)	T_{AIR} (°F)	T_{H_2O} (°F)	Barometric Pressure (in. Hg)
100 x 100 Truncated Cone (Contd.)									
432	0.688	19	24.1	0.0129	0.952	0.0089	90.3	87.5	29.40
433	0.688	13	24.1	0.0170	0.952	0.0117	90.5		
434	0.718	7	23.1	0.0277	0.912	0.0199	90.5		
435	0.232	19	32.7	0.044	1.29	0.0102	90.2		
436	0.232	13	32.8	0.0860	1.30	0.0200	90.1		
437	0.232	7	32.7	0.1634	1.29	0.0379	90.0		
438	0.742	19	32.2	0.0527	1.27	0.0391	90.0		
439	0.742	13	32.2	0.0652	1.27	0.0484	89.9		
440	0.726	7	32.9	0.1004	1.30	0.0729	89.8		
Straight Riser									
441	0.231	19	32.9	0.191	1.30	0.0441	88.6	87.5	29.40
442	0.227	13	33.4	0.217	1.32	0.0492	88.6	88.0	
443	0.232	7	32.7	0.256	1.29	0.0593	88.5	89.0	
444	0.734	19	32.7	0.091		0.0667	88.5	89.0	
445		13	32.7	0.097		0.0713	88.1	89.0	
446		7	32.7	0.122	1.45	0.0899	88.1	90.5	
447	0.207	19	36.6	0.154		0.0319	82.0	84.5	
448		13		0.244		0.0505	82.4	86.0	
449		7		0.313		0.0648	82.6	87.5	
450	0.656	19		0.107		0.0702	82.9	89.0	
451		13		0.118		0.0773	83.2	90.0	
452		7		0.140		0.0918	83.2	90.5	
453	0.223	19	23.8	0.064	0.94	0.0413	84.5	87.0	
454	0.223	13		0.074		0.0164	84.5	87.0	
455	0.223	7		0.104		0.0231	84.6	87.5	
456	0.668	19		0.038		0.0256	84.9		
457		13		0.043		0.0286	85.0		
458		7		0.057		0.0378	85.1		
100 x 100 Inverted Cone									
459	0.1367	19	37.3	0.00319	1.47	0.000436	88.3	84.0	29.35
460		13		0.00682		0.000933	88.0	84.5	
461		7		0.0812		0.00111	87.5	85.0	
462		4		0.384		0.00525	87.1	85.0	
463	0.4263	19		0.0164		0.00699	86.9	84.5	
464		13		0.0236		0.0108	86.8		
465		7		0.0950		0.0405	86.6		
467		4		0.1906		0.08123	86.6	85.5	
468	0.7071	19		0.0252		0.1783	86.4	84.5	
469	0.7071	13		0.0435		0.03083	86.4	84.5	
470	0.7104	7		0.1067		0.07586	86.4	85.0	
471	0.9893	19		0.0401		0.03968	85.9	82.0	
472	0.9893	13		0.0612		0.06059	85.7	82.0	
473	0.9893	7		0.1547		0.1531	85.6	82.0	
474	1.292	19		0.0529		0.06836	85.1	81.0	
475		13		0.0763		0.09866	85.0	81.0	
476		7		0.1556		0.201	85.0	81.5	
477	0.214	19	32.7	0.0	1.29	0.0	81.8	84.5	
478		13		0.0		0.00	81.8	84.5	
479		7		0.0187		0.00401	82.0	86.0	
480		4		0.1350		0.02896	82.1	86.0	
481	0.489	19		0.0023		0.00113	82.2	84.5	

MECHANICAL REDUCTION OF CARRYUNDER DATA (Contd.)

Run No.	X_R ($\times 10^{+3}$)	H (in.)	$\dot{W}_\ell$ (lb/sec)	X_D/X_R	V_{SD} (ft/sec)	X_D ($\times 10^{+3}$)	T_{AIR} (°F)	T_{H_2O} (°F)	Barometric Pressure (in. Hg)
100 x 100 Inverted Cone (Contd.)									
482	0.489	13	32.7	0.0044	1.29	0.00214	82.5	84.5	29.35
485	0.810	19		0.00626		0.00507	83.5	85.0	
486		13		0.0161		0.01306	83.7	85.0	
487		7		0.0524		0.04251	83.9	86.0	
483	0.486	7		0.0537		0.02614	84.4	87.0	29.24
484	0.486	4		0.117		0.05688	84.4	88.5	
488	1.17	19	31.5	0.0085	1.3	0.00994	85.4	86.5	
489	1.117	13	33.0	0.0240		0.02680	85.4	87.5	
490	1.120	7	32.9	0.0579		0.06484	85.3	86.5	
491	1.113	19	33.1	0.0148		0.01647	85.8	85.5	
492	1.443	19	33.2	0.0108		0.01558	86.1	86.5	
493	1.452	13	33.0	0.0280		0.04065		86.5	
494	1.452	7	33.0	0.0436		0.06331		88.5	
495	0.300	13	24.0	0.0	0.95	0.0	76.0	84.5	29.89
496	0.661	19	23.7	0.0		0.0	76.6		
497	0.650	13	23.8	0.0		0.0			
498	0.654	7	23.8	0.00164		0.00107			
499	1.125	19	23.7	0.00052		0.00058	76.6		
500	1.115	13	23.9	0.000985		0.00109	77.0		
501	1.115	7	23.9	0.00487		0.00543	77.2		
502	1.541	19	23.9	0.00081		0.00124	77.4	82.5	
503	1.534	13	24.0	0.0027		0.00414	77.6		
504	1.541	7	23.9	0.00565		0.00870	77.6		
505	2.00	19	24.0	0.00171		0.00342	77.5		
506	2.00	13		0.00377		0.00754	77.5		
507	2.21	19		0.00152		0.00335	77.7		
508	2.21	13		0.00348		0.00764	77.9		
Perforated Metal									
511	0.731	19	36.6	0.0454	1.50		77.1	82.0	29.45
512	0.731	13	36.6	0.0804	1.50		77.1	82.0	29.45
60 x 60 Inverted Cone									
515	0.728	19	36.6	0.0903	1.5		77.8	83.0	29.40
517	0.721	13	37.0	0.1085	1.5		77.3	83.0	29.40
518	0.721	13	37.0	0.1085	1.5		77.3	83.0	29.40
40 x 30 Inverted Cone									
520	0.719	19	37.2	0.0848	1.5	0.061	74.1	81.5	29.35
521	0.719	13	37.2	0.0997	1.5	0.071	74.1	81.5	29.35
100 x 100 Inverted Cone									
524	0.719	19	37.2	0.0353	1.5	0.025	78.0	84.0	29.35
525	0.719	13	37.2	0.0564	1.5	0.040	78.0	84.0	29.35
528	0.719	7	37.2	0.0919	1.5	0.066	78.0	84.0	29.35
120 x 120 Inverted Cone									
529	0.719	19	37.2	0.04373	1.5		79.5	83.0	29.35
531	0.719	13	37.2	0.0615	1.5				
532	0.719	7	37.2	0.1285	1.5				

APPENDIX B

PHOTOGRAPHS

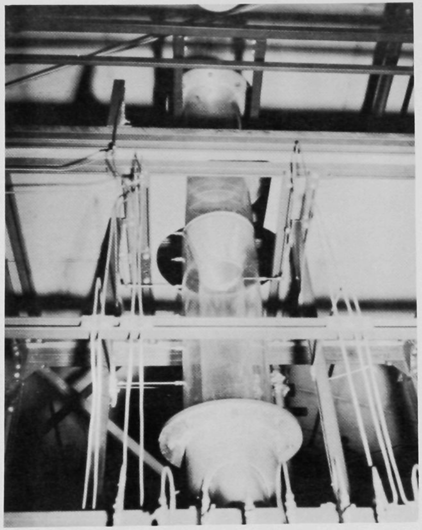


Fig. B-1. Test Section with Inverted Conical Screen Installed on Top of Riser.

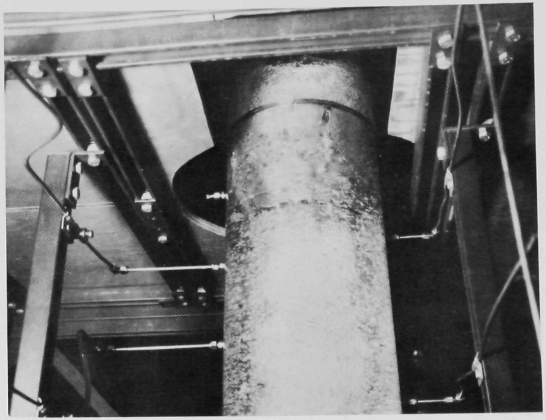


Fig. B-2. Test Section under Operating Conditions

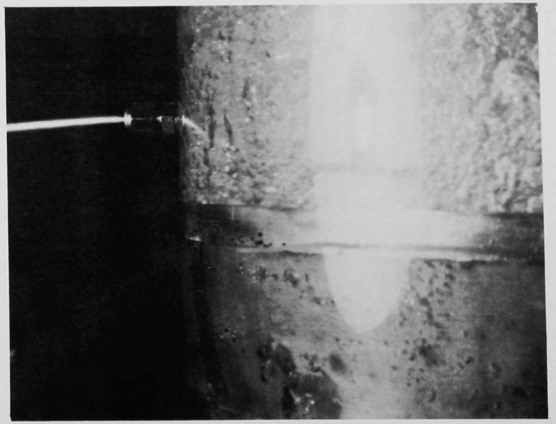


Fig. B-3. Close-up View of Screen on Top of Riser

APPENDIX C

DIMENSIONAL EMPIRICAL CORRELATION

In a previous report,(1) an empirical correlation was determined for carryunder in both air-water simulated boiling and steam-water boiling systems. This correlation was determined with data taken from three different system arrangements. There were two air-water simulated boiling systems: one with a $3\frac{1}{4}$-in. diameter riser and a $5\frac{1}{2}$-in.-diameter downcomer, and one with a $5\frac{1}{2}$-in.-diameter riser and a $9\frac{1}{4}$-in.-diameter downcomer. The steam-water boiling system consisted of a 3-in.-diameter, thin-wall riser section and a 6-in., schedule 160 outer pipe acting as a downcomer. All three systems were geometrically similar in that the ratio of areas, downcomer to riser, was approximately two.

The correlation presented as Fig. C-1 includes the following parameters and parameter ranges:

For the air-water simulated boiling system:

Riser void fraction	α_R	0.10-0.50
Downcomer velocity	V_{SD}	$\frac{1}{2}$-$2\frac{1}{2}$ ft/sec
Riser quality	X_R	0.0002-0.003
Height of interface	H	4-19 in.
Area ratio between downcomer and riser	A_D/A_R	1.70

For the steam-water boiling system:

Riser void fraction	α_R	0.10-0.50
Downcomer velocity	V_{SD}	$\frac{1}{2}$-$2\frac{1}{2}$ ft/sec
Height of interface	H	6-15 in.
Pressure	P	600, 1000, and 1500 psi
Area ratio between downcomer and riser	A_D/A_R	2.0

New System Geometry

The system used to determine the effect of goemetry on the correlation of Fig. C-1 consisted of a $9\frac{3}{8}$-in.-OD, $9\frac{1}{4}$-in.-ID, stainless steel riser, and the downcomer was an $11\frac{1}{8}$-in.-ID Lucite plastic pipe. The ranges of parameters studied were:

Riser void fraction	α_R	0.04-0.20
Downcomer velocity	V_{SD}	$1\text{-}2\frac{1}{2}$ ft/sec
Riser quality	X_R	0.0002-0.002
Height of interface	H	11 in.
Area ratio between downcomer and riser	A_D/A_R	0.42

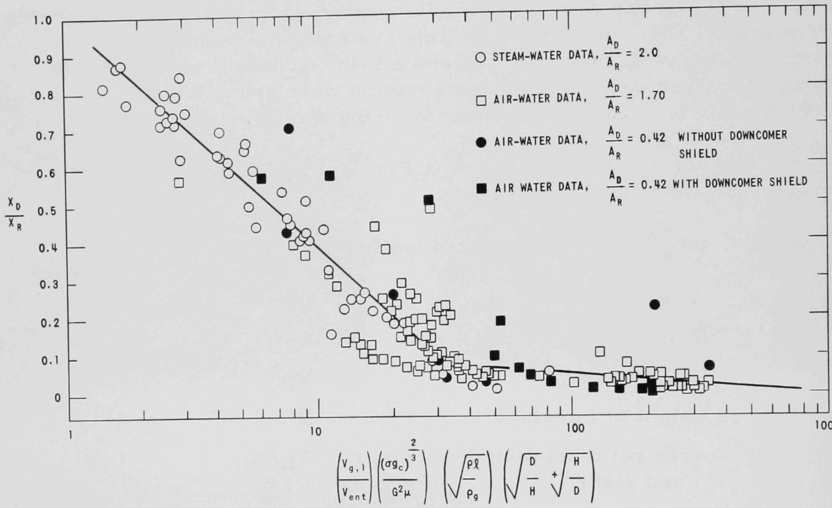


Fig. C-1. Dimensional Correlation of Carryunder Data

The first series of data were taken with the test section as represented in Fig. C-2. These data are shown in Fig. C-1 as solid circles. It is apparent that the data fit the correlation fairly well. However, two difficulties were encountered that need more investigation before a definite conclusion can be reached.

The first of these difficulties was encountered as a result of the small ratio of areas. The annular downcomer space was only $\frac{7}{8}$ in. wide, and this resulted in the formation of a large gas pocket in the space where the downcomer void readings were taken. The mixture coming from the riser cascaded down over the edge of the riser, as shown schematically in Fig. C-3, which made void readings useless at all downcomer superficial liquid velocities greater than approximately 1 ft/sec.

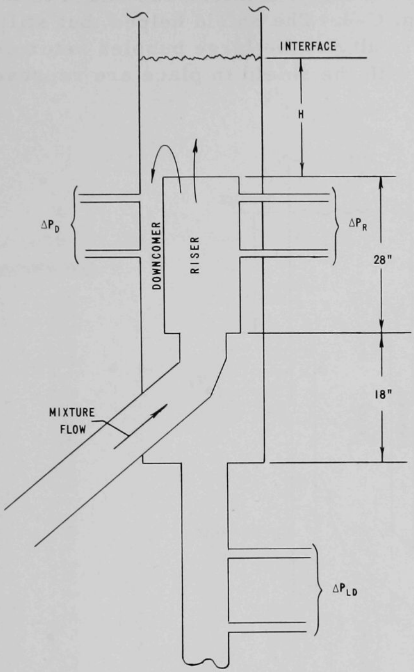


Fig. C-2. Cross-sectional View of Test Section

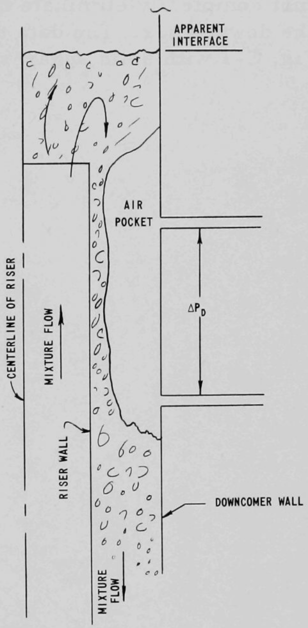


Fig. C-3. Flow Pattern in Downcomer

Because of this difficulty, it was necessary to take downcomer void readings at the lower downcomer void fraction pressure taps, and these are the readings used in the data presented in Fig. C-1. This procedure does not correspond with that used by Petrick,[1] who used the upper downcomer void readings in establishing the original correlation.

The second difficulty encountered was due to the physical construction of the apparatus. The lower downcomer region formed a chamber where the flow cross-section area was momentarily increased by a factor of about three. This resulted in a correspondingly decreased superficial liquid velocity, which in turn permitted the relatively small gas bubbles to coalesce into much larger bubbles which had enough buoyancy to return up the downcomer. This return of the large bubbles was not a steady process, but occurred periodically with a great deal of turbulence and disruption of flow patterns.

To eliminate this coalescing chamber, a shield was added to the bottom of the riser, as shown in Fig. C-4. The shield helped, but still did not completely eliminate the difficulty of the large bubbles returning up the downcomer. The data taken with the shield in place are represented in Fig. C-1 with solid squares.

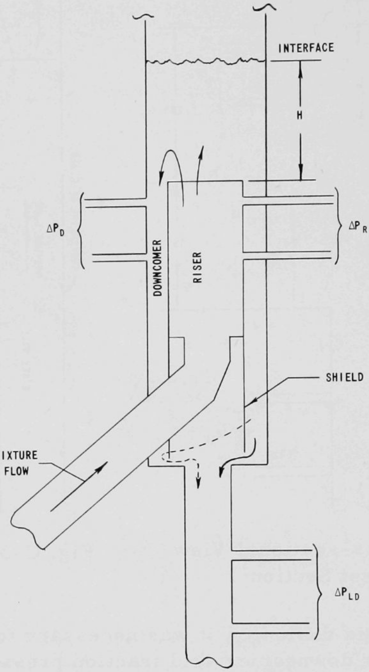


Fig. C-4. Cross-sectional View of Modified Test Section

These data fit the correlation well at moderate carryunder conditions, which are those involving low downcomer superficial liquid velocities. As shown by Petrick[1] and earlier in this report, a low downcomer velocity is desirable in order to reduce carryunder, all other things being equal.

In the higher carryunder region, above approximately 20 percent, the data become unreliable due to previously mentioned difficulties.

DIMENSIONAL CORRELATION DATA

Riser ID = 9.25 in.
Riser OD = 9.37 in.
Downcomer ID = 11.125 in.

Run No.	X_R ($\times 10^{+3}$)	H (in.)	$\dot{W}_\ell$ (lb/sec)	X_D/X_R	V_{SD} (ft/sec)	α_R	α_D	X_D ($\times 10^{+3}$)	T_{AIR} (°F)	T_{H_2O} (°F)	Barometric Pressure (in. Hg)
No Downcomer Shield											
312	0.205	19	11.2	0.0	0.92	0.044	0.046	0.0	79	78	29.55
313	0.223	15				0.042	0.050				
314	0.205	11				0.058	0.054				
315	0.205	7				0.044	0.062				
316	0.205	4				0.044	0.088			79	
317	0.625	4				0.106	0.123				
318	0.625	11				0.106	0.098				
319	0.625	19	11.3		0.93	0.102	0.087				
320	1.000	19	11.2		0.92	0.135	0.104		82	82	
321	1.000	11	11.3		0.93	0.143	0.121				
322	1.000	4				0.139	0.146				
323	1.491	4				0.185	0.167				
324	1.491	19				0.181	0.121				
325	1.991	19				0.200	0.123				
326	1.991	4	11.4			0.191	0.210				
327	0.184	4	15.2		1.25	0.0437	0.139				
328	1.980	19	15.1	0.0013	1.24	0.2232	0.1564	0.0026	80.0	80.5	29.45
330	0.200	7	23.9	0.2298	1.96	0.0521	0.4776	0.0049	80.0	84.1	29.45
331	0.600	11	23.7	0.0723	1.96	0.1502	0.6883	0.0462	80.0	85.0	29.45
332	1.000	11	23.8	0.0325	1.95	0.1835	0.2294	0.0332	80.2	84.3	29.45
333	1.240	15	24.0	0.0256	1.97	0.2106	0.2086	0.0324	80.5	84.3	29.45
334	0.211	11	23.7	0.2638	1.96	0.0667	0.0646	0.0567	80.5	81.0	29.35
335	0.633	11	23.9	0.0901	1.96	0.1293	0.0646	0.0580	80.6	84.7	29.35
336	0.999	11	24.0	0.0464	1.97	0.1835	0.0521	0.0472	80.5	84.7	29.35
338	1.254	11	23.9	0.0338	1.96	0.2148	0.0626	0.0431	80.5	85.5	29.35
339	0.225	11	35.8	0.7085	2.93	0.0480	0.1105	0.1170	81.0	84.3	29.35
340	0.419	11	36.0	0.4370	2.95	0.1231	0.1731	0.1875	82.0	84.3	29.35
With Downcomer Shield											
341	0.195	11	11.3	0.0000	0.93	0.0438	0.0042	0.000	77.5	76.0	29.50
342	0.620	11	11.3	0.0057		0.1126	0.0062	0.0004	77.5	76.0	
343	1.000	11	11.3	0.0007		0.1460	0.0062	0.0007	78.0	76.0	
344	1.469	11	11.3	0.0006		0.1839	0.0115	0.0009	78.0	76.0	
345	1.982	11	11.3	0.0004		0.2210	0.0115	0.0007	78.5	75.0	
346	0.200	11	15.0	0.0133	1.23	0.0459	0.0062	0.0027	78.5	74.0	
347	0.633	11	15.0	0.0076	1.23	0.1251	0.0124	0.0048	78.0	74.0	
348	0.860	11	15.1	0.0071	1.24	0.1585	0.0146	0.0060	79.0	74.0	
349	1.500	11	15.1	0.0049	1.24	0.2127	0.0167	0.0072	79.5	74.0	
350	0.240	11	20.0	0.1006	1.64	0.0584	0.0438	0.242	82.0	75.0	
351	0.755	11	20.0	0.0450	1.64	0.1564	0.0705	0.338	82.5	77.5	
352	1.195	11	19.9	0.0297	1.63	0.2088	0.0715	0.357	82.5	80.6	
353	0.287	11	24.7	0.1822	2.02	0.0834	0.1606	0.052	82.5	85.5	
354	0.923	11	24.6	0.0703	2.02	0.1839	0.1627	0.064	82.5	84.0	
355	0.206	15	34.4	0.5715	2.82	0.0542	0.0736	0.118	82.5	84.0	
356	0.410	22	34.6	0.4924	2.84	0.1084	0.5736	0.117	82.5	84.0	
357	0.410	22	34.6	0.5029	2.84	0.1084	0.5632	0.206	82.5	84.0	
358	0.211	22	34.6	0.5796	2.84	0.0500	0.1251	0.128	82.5	81.5	

ACKNOWLEDGMENT

The authors wish to express their thanks to Dr. Michael Petrick for defining the problem and giving continuous advice. Mr. P. L. Zaleski was especially helpful in designing and constructing the many modifications to the system, the taking of data, and in providing an insight into the peculiarities and limitations of the system.

BIBLIOGRAPHY

1. Michael Petrick, A Study of Vapor Carryunder and Associated Problems, ANL-6581 (July 1962).